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Estimating Critical Climate-Driven Thresholds in Landscape Dynamics Using Spatial Simulation Modeling: Climate Change Tipping Points in Fire Management

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I. Abstract

Climate projections for the next 20-50 years forecast higher temperatures and variable precipitation for many landscapes in the western United States. Climate changes may cause or contribute to threshold shifts, or tipping points, where relatively small shifts in climate result in large, abrupt, and persistent changes in landscape patterns and fire regimes. Rather than simulate potential climate-fire interactions using future climate data derived from Global Climate Models (GCMs), we developed sets of progressively warmer and drier or wetter climate scenarios that span and exceed the range of GCM outputs for the western US, including temperature and precipitation combinations that may not be present in GCM projections by may occur at finer (regional or local) scales. These climate scenarios were used to simulate potential future fire and vegetation dynamics in three study areas in the western United States - McDonald watershed, Glacier National Park (MT), the central plateau of Yellowstone National Park (WY), and the East Fork Bitterroot River basin (MT). These landscapes encompass a diverse range of biophysical settings, vegetation species, forest structure, and fire regime, and thus were expected to differ in their sensitivity to climate changes and exhibit unique threshold behavior following climatic and wildfire perturbations. Each of the study areas proved sensitive to simulated changes in temperature and precipitation, as reflected in shifts in mean annual burned area, crown fire area, and fire-caused tree mortality. Sensitivity to climate changes differed across landscapes – for example, a significant decline in basal area occurred at temperature shifts of 3 °C and above for the Yellowstone National Park study area, 4 °C and above for the Glacier National Park study area, and above 5 °C for the East Fork Bitterroot River basin. Moreover, shifts in basal area were strongly related to changes in area burned and fire regime characteristics, suggesting that synergistic interactions of climate and fire will be important in determining future landscape patterns.

II. Background and purpose

Climate change is projected to profoundly influence landscape patterns and biotic community compositions either directly through increased species mortality and shifts in species distributions, or indirectly through processes such as increased wildfire activity and extent, shifting fire regimes, and pathogenesis (Flannigan et al. 2000, Dale et al. 2001, Lenihan et al. 2003, McKenzie et al. 2004, Bentz et al. 2010). Forests of the western United States are expected to experience significant impacts in response to projected future climate change, particularly in mountainous ecosystems (Fagre and Peterson 2000). Comparison of climate projections with plant-climate profiles for the region suggests that by the end of the 21st century approximately 47 percent of the landscape may experience climate conditions outside of the current analog, resulting in an increase in montane forest and grassland communities at the expense of subalpine, alpine, and tundra ecosystem types (Rehfeldt et al. 2006). Recent research shows that background tree mortality rates in the western United States have increased rapidly in recent decades, likely as the result of regional warming and increased water stress (van Mantgem et al. 2009). Widespread tree mortality, species range shifts, and changes in disturbance regimes have potentially severe negative consequences for biodiversity, wildlife habitat, snowpack accumulation and retention, timing and amount of surface water runoff, and carbon sequestration (Fagre and Peterson 2000, Tomback and Achuff 2010). Climate-mediated shifts in terrestrial ecosystems are occurring in the context of other long-term anthropogenic influences such as land use change, resource development, and forest management. These interactions may further serve to shift ecosystems away from current conditions (Dale et al. 2001).

Climate projections for the next 20-50 years forecast higher temperatures and variable precipitation for many landscapes in the western United States (IPCC 2007). These changes will likely result in prolonged drought, longer fire seasons, and lower fuel moistures that may, in turn, foster more frequent, larger, and more severe wildfires (Running 2006). The important questions that many fire managers are now asking are ***"What may fires and fire effects be like in the future, and how will climate changes and changes in fires affect our management response?"*** To address this question many ecosystem and fire modelers are using gridded climate data generated and synthesized from one or more Global Climate Models (GCMs) to simulate climate interactions with vegetation and disturbance across landscapes (Bachelet et al. 2001, Neilson et al. 2005). These gridded climate data sets may not always be the best tools for driving regional models because 1) different GCMs produce very different and highly uncertain results, 2) GCMs presume carbon emissions scenarios that may be inconsistent with future emissions profiles (e.g., increased emissions over expected levels), 3) carbon budgets and dynamics for many oceanic and terrestrial ecosystems are not fully described or understood, and 4) even downscaled (regional-scale) GCMs may not account for complex climate-landform interactions, such as topographical effects on temperature and precipitation patterns, that produce unique local climate and weather patterns. In addition, the uncertainty in these climate scenarios is high because of errors or limitations in GCM design and parameterization, inability to forecast future rates of carbon emissions, and inconsistent downscaling methods.

We developed an alternative approach based on climate thresholds: progressively warmer and drier or wetter climate scenarios that span and exceed the range of GCM outputs. By systematically varying those weather variables that describe climate, we identified tipping points, or ecological thresholds, where incrementally small changes in climate resulted in large, abrupt, and persistent changes in landscape and fire regimes. Knowledge of potential tipping points allows managers to plan for changes in fire severity and frequency that may occur when the climate reaches a predetermined threshold. Management actions such as fuel treatments or prescribed fire can be implemented in anticipation of tipping points to mitigate adverse effects of climate change on landscape structure and function. Simulation models using GCM-based climate predictions rather than the method described here may miss those tipping points critical for landscape and fire management, and therefore limit the ability of land managers to respond to climate change threats.

III. Study description and location

Simulation model

FireBGCv2 is a cumulative effects, or regime, model developed to assess long-term trends in landscape ecological patterns and processes. The model is not intended as a prognostic tool for near-future predictions, but is best used to simulate interactions of disturbance, climate, and vegetation across ecological (centuries) time scales. Because the FireBGCv2 model contains many stochastic elements results must be summarized across multiple model replicates to determine trajectories of landscape behavior and response, and results are best compared in a relative framework across multiple scenarios (Keane et al. 2011). Model simulations are typically run for many hundreds of years, but these simulation periods are not intended to produce forecasts that correspond to calendar years. Rather, the simulation period represents the range and variability in ecosystem response that is possible given a set of climate drivers.

The FireBGCv2 modeling platform combines a mechanistic, individual tree succession model with a spatially explicit fire model incorporating ignition, spread, and effects on ecosystem components, all with stochastic properties implemented in a spatial domain (Keane et al. 1996, Keane et al. 1998, Keane et al. 1999, Keane et al. 2011). The model is designed around five hierarchical levels of spatial organization from coarse, fixed-boundary sites defined by similar topography, weather, soils, and potential vegetation; to dynamically-created stands that differ by existing vegetation composition and structure; to simulation plots on which ecosystem processes are modeled for computational efficiency; to species with well-defined physiological parameters; to individual trees, each of which is explicitly represented with attributes such as age, height, diameter at breast height (DBH), and height to live crown. The model is a useful tool for evaluating climate change impacts on species because climate and weather explicitly influence vegetation through temperature and moisture controls on establishment, growth, and mortality, and timing and severity of disturbance processes.

The ecophysiological algorithms that drive the FireBGCv2 model have been described in detail elsewhere (Running and Coughlan 1988, Running and Hunt 1993, Keane et al. 2011). Briefly, tree growth is simulated using the complex interactions of daily temperature, precipitation, attenuated radiation, and soil moisture. For each species in the model thermal limits are defined by minimum, maximum, and optimal ranges. Temperatures outside of these ranges affect trees through a reduction in the annual growth increment and eventual mortality. Tree regeneration is driven by soil moisture, litter depth, and long-term climate-influenced cone crop production. Long-term temperature and precipitation data are used to compute fire ignitions, and daily weather drives fuel moistures that dictate fire spread. Moreover, there are complex feedbacks among climate, disturbance, and vegetation; for example, fire dynamics are responsive to long-term interactions of climate and vegetation that determine spatial and temporal patterns of fuel availability. Potential FireBGCv2 model outputs include an large array of stand-level variables describing vegetation characteristics such as basal area, leaf area index, and carbon compartments; fuel characteristics such as woody and non-woody fuel loadings; and individual fire characteristics such as area burned and fireline intensity (Keane et al. 2011).

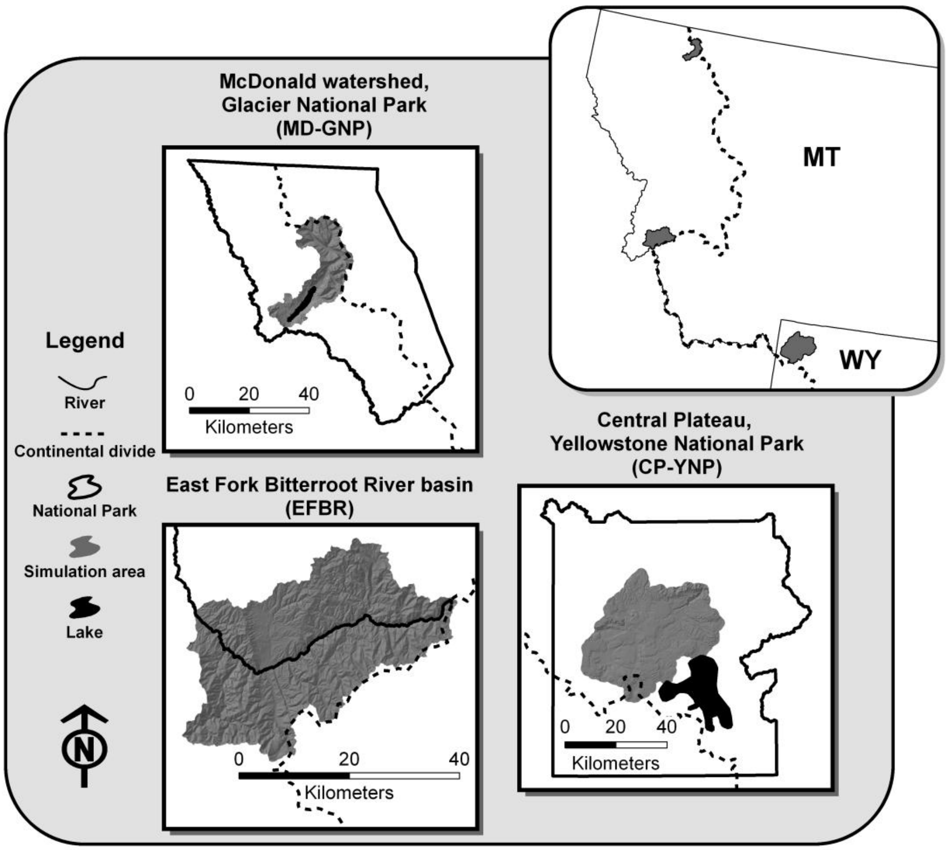
Study design

We implemented a factorial experiment with temperature and precipitation as factors. Temperature change factors ranged from one to six degrees Celsius (°C) in one degree steps and precipitation change factors ranged from 70 percent to 130 percent in 10 percent increments, resulting in 42 climate change scenarios. We used combinations of temperature and precipitation factors to adjust long-term, daily baseline instrumental weather acquired from National Climatic Data Center cooperative weather stations (NCDC 2011). Climate offsets were applied evenly across four seasons to adjust baseline weather. We additionally simulated a null, or no climate change scenario for each simulation landscape. We simulated 10 replicates per scenario to account for the stochastic nature of many model processes including cone crop abundance, tree mortality, and wildfire origination and extent. Simulations were run for a 600-year period, approximately twice the length of the longest expected historic fire return intervals for the study areas (Agee 1998). We used a parsimonious list of output variables to evaluate changes in vegetation and fire regimes including basal area, area burned, crown fire area, and fire-caused tree mortality. All simulations were performed for natural fire conditions (e.g. no fire suppression, prescribed fire, or other fire or fuels management. We did not simulate dynamics of white pine blister rust, mountain pine beetles, or other pests or pathogens that are common mortality agents within forested landscapes of the northern Rocky Mountains (Dale et al. 2001, Logan and Powell 2001, Bentz et al. 2010), as we wanted to isolate the interactive effects of climate and fire on vegetation transition and post-disturbance recovery. All simulations were performed on a 144-processor Cray supercomputing cluster operating in the Linux computing environment.

Study areas

We simulated potential tipping point responses on three landscapes in the western United States: the McDonald watershed of Glacier National Park, Montana (MD-GNP), the central plateau region of Yellowstone National Park, Wyoming (CP-YNP), and the East Fork of the Bitterroot River basin, Montana (EFBR) (Figure 1). Although all are located within the intermountain region of the western United States and contain fire-prone and fire-adapted forest types, these landscapes represent different biophysical settings and are characterized by differences in vegetation species composition, forest structure, and fire regime; thus, they were expected to differ in their sensitivity to climate changes and exhibit unique threshold behavior following climatic and wildfire perturbations.

Figure 1. Simulation landscapes.



McDonald watershed, Glacier National Park, Montana

The MD-GNP study area is a 43,000 ha watershed located in northwestern Montana, USA between 48° 30'N and 48° 51'N and between 113° 42'W and 114° 5'W. The watershed is a long, narrow, glaciated valley that contains a large lake at its base and is surrounded by rugged mountains. Elevations range from 830 to 2,900 meters above sea level (masl). Climate within the MD-GNP watershed is mainly inland-maritime with cool, wet winters and short, warm-dry summers (Finklin 1986). Climax vegetation zones consist of low-elevation forests of western hemlock and western red cedar in relatively, warm, moist lakeside environments and western larch (*Larix occidentalis*), interior Douglas-fir, and lodgepole pine (*Pinus contorta* var. *contorta*) in drier low-elevation areas (Habeck 1970b, Kessell 1979). Upper subalpine forests consist primarily of subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*), and whitebark pine (*Pinus albicaulis*) (Habeck 1970b). Alpine environments (2,200 masl and above) support Krummholz conifer and forb meadow communities (Habeck and Choate 1963). Fire regimes include large, stand-replacement fires on moist sites and surface fires with approximately on drier areas of the watershed, both of which occur at long intervals (Habeck 1970a, Barrett 1986, Barrett et al. 1991). The complex topography of MD-GNP has considerable influence on fire behavior and effects via the spatial arrangement of fuels on the landscape. Rocky areas with low accumulation of woody fuels impede fire spread across and within the watershed, and moist conditions on north-facing slopes often prevent spread of fire from the drier south-facing slopes (Habeck 1970b).

Central plateau region, Yellowstone National Park, Wyoming

The CP-YNP landscape, located in northwestern Wyoming, is approximately 154,000 ha in area. The study area is located between 44° 24'N and 44° 50'N and between 110° 16'W and 110° 56'W and includes much of the central plateau region of Yellowstone National Park. The central plateau is a high elevation (2,000-3,000 masl) forested region with a distinct climate characterized by short cool summers and long, cold winters, with precipitation occurring in all seasons with the greatest accumulation in winter and spring (Despain 1987). The landscape is dominated by even-aged lodgepole pine (*Pinus contorta spp. latifolia*) forests with lesser spruce-fir (*Picea engelmannii, Abies lasiocarpa*), whitebark pine (*Pinus albicaulis*), Douglas-fir (*Pseudotsuga menziesii*) components (Despain 1990). Wildfires are an integral part of the ecological process and pattern of the Yellowstone plateau. Fire history and forest demography studies show evidence for large stand-regenerating fires at long intervals, interspersed with fewer small and short-interval fires (Romme 1982, Millspaugh et al. 2000). Large fires, accounting for most of the total area burned over the last several centuries, have created a mosaic of stands in various stages of post-fire succession, from recently burned stands dominated by dense lodgepole pine seedling clusters to middle-stage, even-aged closed canopy stands that include a developing spruce-fir understory, to late-successional mixed conifer forests of uneven age (Romme and Despain 1989).

East Fork Bitterroot River basin, Montana

The East Fork Bitterroot River (EFBR) basin is a 105,487 ha watershed within the Bitterroot National Forest located in west-central Montana, USA between 45° 41'N and 46° 2'N and between 113° 30'W and 114° 10'W. The EFBR is a temperate, snowmelt-dominated basin with relatively high elevation (1,225 to 2,887 masl) and dry conditions, with most precipitation falling as snow from November to March. The basin is a mainly forested landscape (80%) with lower elevations composed of ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii)* and higher elevations consisting of lodgepole pine (*Pinus contorta* var. *latifolia),* subalpine fir *(Abies lasiocarpa),* and Engelmann spruce (*Picea engelmanii.* The historical fire regime for this area is best described as mixed–severity (Arno et al. 2000) with short intervals between fires that are generally of low-to-medium intensity except in steep terrain (Arno 1976).

IV. Key findings

We assessed potential threshold shifts resulting from climate changes using exploratory data analysis and statistical tests performed in the R statistical software package (R Development Core Team 2010). We focused on changes in mean area burned (sum of fire sizes across all fire years and replicates divided by 6,000 total simulation years per scenario) and crown to surface fire ratio as indicators of fire regime characteristics, fire-caused tree mortality (area weighted mean percent of trees killed in fires) as a proxy indicator for fire severity, and basal area (ending year simulation values averaged across replicates for each scenario) as an indicator of landscape functional type (e.g. forest, shrub, or grassland dominants).

Key Finding 1: Mean annual area burned increased with increasing temperature and decreasing precipitation for all landscapes.

Fire sizes and fire frequency are adjusted from parameterized values via changes in the Keetch-Byram Drought Index (KBDI), an index based on daily water balance that is used to determine forest fire potential (Keetch and Byram 1968), such that warm-dry conditions result in moisture depletion, high KBDI values and an upward adjustment to modeled fire size and frequency. The adjustment method provides a simplified model mechanism through which climate changes can directly influence fire regime characteristics, posited to occur from increases in lightening activity, drying or drought periods, fire weather severity, and-or fire season length (Flannigan et al. 2000, Westerling et al. 2006). Larger potential fire sizes and more frequent fires can result in greater burned areas, if sufficient fuel loads exist to carry fire. Annual area burned increased with increasing temperature and decreasing precipitation for all landscapes as expected (Figure 2a). Precipitation appeared to offset some effects of increased temperature, especially for temperature offsets of 5 ºC and above. For all landscapes mean annual burned area was highest for the warmest-driest climate scenario.

Key Finding 2: Climate changes influenced fire-caused tree mortality, with differences among landscapes.

We used tree mortality as an indicator of fire severity, or net ecological impact (Agee 1993). Fire-caused tree mortality in FireBGCv2 occurs with foliage scorch or total consumption, dependent on scorch height, and lethal cambial stem and root damage, dependent on bark thickness (Keane et al. 2011). The degree of crown scorch and cambial kill depends on fire intensity and duration (Ryan and Reinhardt 1988); thus, the fire-caused tree mortality variable integrates physiological attributes of tree species (e.g. thick-barked, high-crowned, fire-adapted tree species such as Ponderosa pine, (Keeley 2012)), as well as fire behavior characteristics such as flame length and environmental characteristics such as wind speed.

Modeled fire-caused tree mortality was responsive to climate changes, with differences in the magnitude and sensitivity of response across simulation landscapes (Figure 2b). For MD-GNP and CP-YNP the highest levels of tree mortality occurred when temperatures were warm, and decreased with increasing temperature and decreasing precipitation. Mortality levels at CP-YNP dropped to ten percent or below with more than 2 ºC increase in temperature for all precipitation offsets, whereas similar levels of mortality in MD-GNP did not occur until temperature offsets increased past 4 ºC. Tree mortality patterns for EFBR were opposite in trend than occurred for the other landscapes, such that tree mortality increased with warmer temperatures, especially temperatures of 5 ºC and above.

Key Finding 3: Climate changes can modify fire regimes and facilitate forest to shrub- and grassland transitions.

Fire regime characteristics described by a combination of area burned and crown to surface fire ratio explain fire-caused tree mortality patterns reported above. Fire regimes in MD-GNP and CP-YNP consist mainly of infrequent, stand-replacing fires – i.e. these landscapes are crown fire dominated systems. The predominance of crown fires over surface fire regimes occurs consistently in these landscapes regardless of simulated climate changes (Figures 3a, 3b). Thus, the highest levels of tree mortality occur when mean annual burned area, most of which burns as lethal crown fires, is sufficiently limited to allow for persistence of forests available to burn throughout the imulations. For climate scenarios with increased mean annual burned area noted above crown fires burn large enough areas in high enough frequency to facilitate a transition from forests to shrub- and grasslands, as indicated by low levels of tree mortality.

In contrast, the fire regime in EFBR consists mainly of non-lethal surface fires and a crown to surface fire ratio of less than 0.10 (tem percent) for all but the warmest simulated temperatures of 5 ºC and above (Figure 3c). Surface fires are not associated with high levels of tree mortality until warm temperatures result in an increase in crown fires, indicated by a crown to surface fire ratio of around 0.20 (20 percent) and above. The shift in fire regimes toward increased crown fire in the EFBR system is sufficient to cause increased tree mortality.

Key finding 4: Forest cover and structure are influenced by changes in climate and fire regimes.

Basal area is an indicator of forest cover and stand structure, with higher basal area values associated with both more forested area and larger-stemmed (mature) trees. The basal area variable integrates the effects of climate and fire on forest cover, as basal area is sensitive to both climate conditions that influence tree growth and survival and effects of climate on burned area and fire regime. Basal area in the three landscapes was highest when crown fires were sufficiently limited in area to allow for the persistence of forested stands, as described above (Figure 2c). Basal area increased slightly with increasing precipitation for temperatures below 4 ºC in MD-GNP, 3 ºC in CP-YNP, and for all temperature change scenarios in EFBR as the result of improved growing conditions and decreased KBDI associated with increased moisture. Increased crown fire activity caused sharp drops in basal area for all landscapes, with temperature thresholds of 3-4 ºC in MD-GNP, 2-3 ºC in CP-YNP, and 5 ºC for EFBR.

Key finding 5: Climate tipping points are different for different landscapes – i.e. some landscapes are more resistant to change than others. Precipitation amount may offset some effects of warming.

The climate thresholds above which a change in basal area occurred are different for each of the three simulation landscapes (Table 1). For MD-GNP mean basal area differed significantly from the no climate change scenario for most temperature changes combined with equal or lesser amounts of precipitation than current conditions. Temperature shifts of 4 °C and above resulted in a significant decrease in basal area regardless of precipitation amount. For temperature shifts of 4 °C and below increased precipitation mediated effects of higher temperatures on basal area. For CP-YNP temperature shifts of 3 °C and above significantly decreased mean basal area, regardless of precipitation amount, and precipitation mediated temperature effects only for moderate levels of warming of 1-2 °C. The EFBR landscape appeared more resistant to climate changes, with uniformly significant decreased basal area for temperature shifts of 5 °C and above, and increased basal area for precipitation equal to or greater than current amounts and temperature shifts of 1-3 °C.

Figure 2. Climate-driven changes in average annual area burned as percent of total landscape area (a), fire-caused tree mortality as percent of total tree mortality (b), and mean basal area (c) for MD-GNP, CP-YNP, and EFBR. Note that scales are unequal across landscapes to account for differences in magnitude of response.

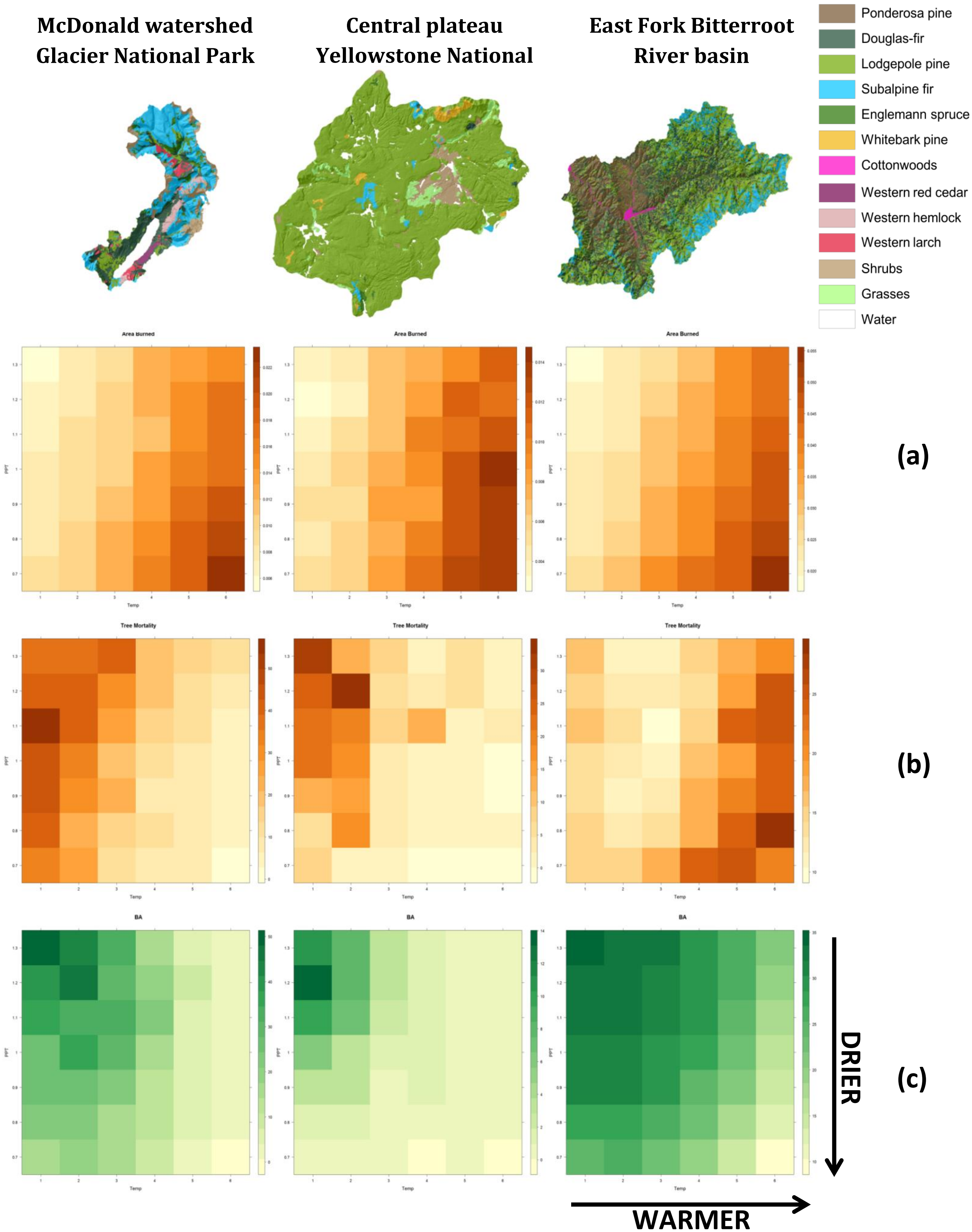
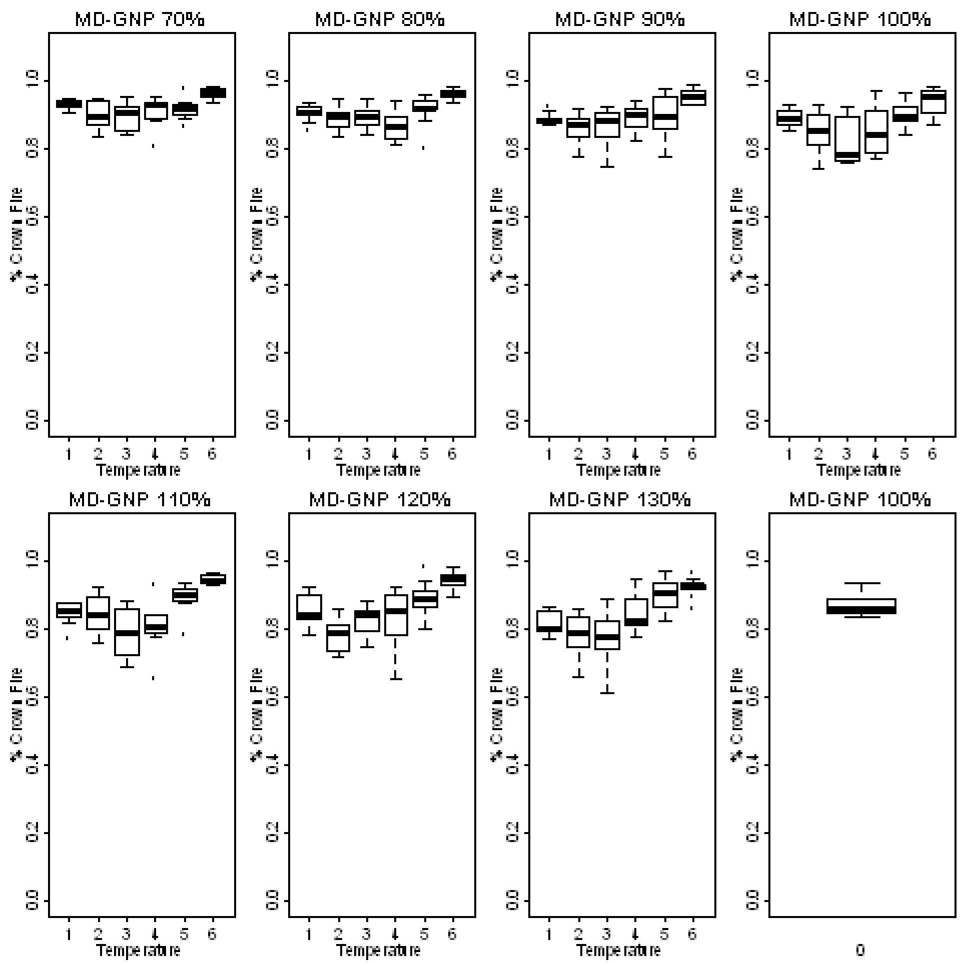
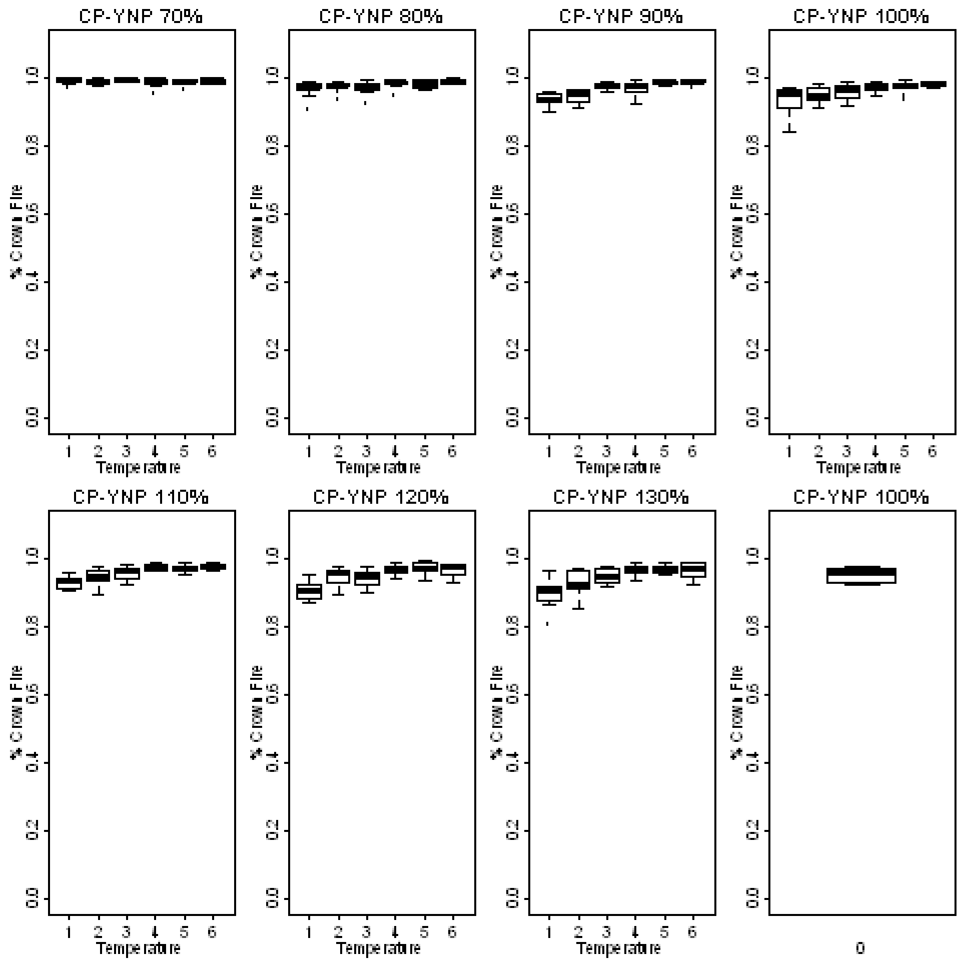


Figure 3. Crown fire to surface fire ratio for simulated climate changes and the no climate change scenario, MD-GNP (a), CP-YNP (b), and EFBR (c).

(a)

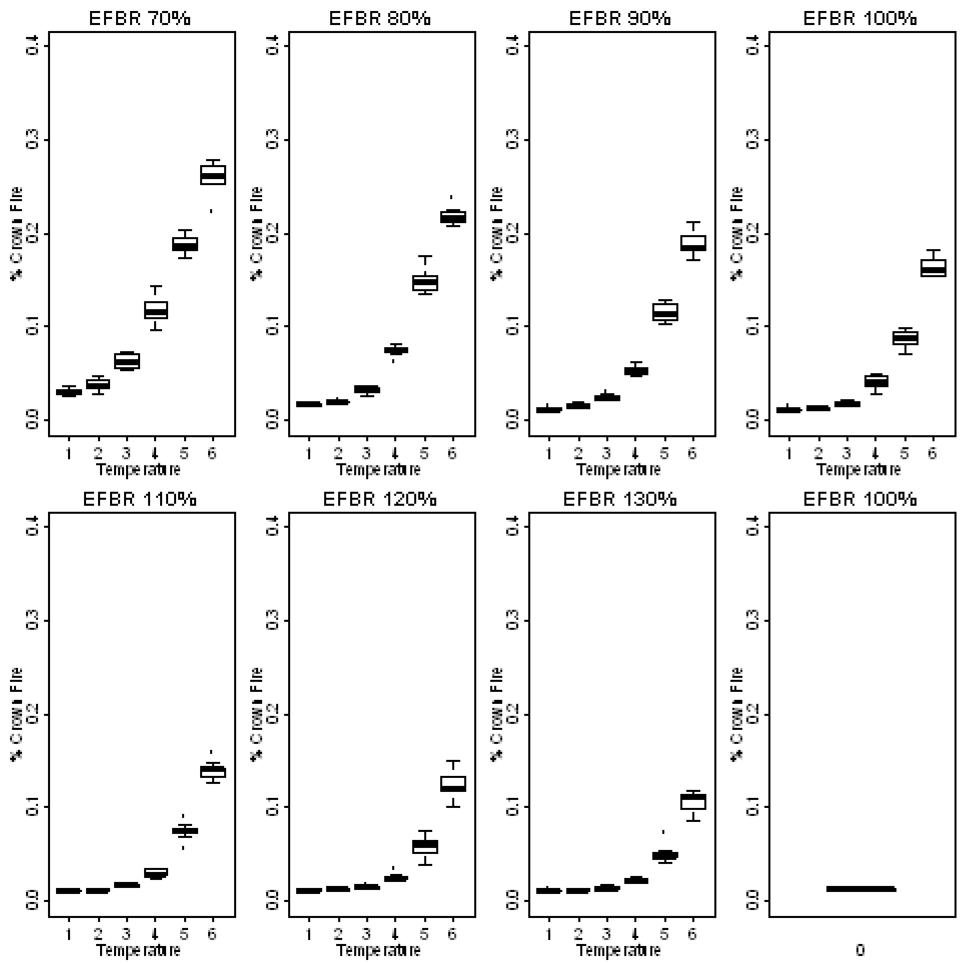


(b)



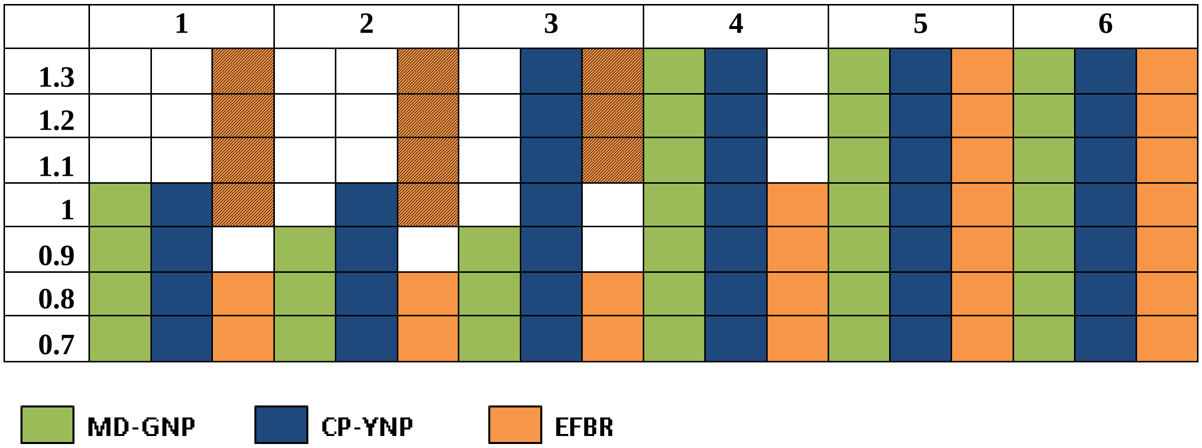
CP-YNP 70%
CP-YNP 80%
CP-YNP 90%
CP-YNP 100%
CP-YNP 110%
CP-YNP 120%
CP-YNP 130%
CP-YNP 100%
% Crown Fire
Temperature

(c)



EFBR 70%
EFBR 80%
EFBR 90%
EFBR 100%
EFBR 110%
EFBR 120%
EFBR 130%
EFBR 100%
% Crown Fire
Temperature
0.0
0.1
0.2
0.3
0.4
1
2
3
4
5
6
0

Table 1. Significant (P < 0.5) changes in mean basal area for climate change scenarios for MD-GNP, CP-YNP, and EFBR. Solid fill indicates decreased basal area and hatched fill indicates increased basal area as compared with the no climate change scenario.



V. Management implications

Implication 1: Future landscapes are likely to be different than landscapes of today.

We observed shifts in mean annual area burned, crown to surface fire ratio, fire-caused tree mortality, and basal area in our study landscapes. These changes were associated with nearly all simulated levels of climate change, but in particular scenarios with both increased warming and increased drying. Such changes are consistent with projections for future climate in the western United States, which is expected to warm by approximately 2-4 °C during the 21st century, with associated increased frequency and persistence of drought conditions (Diffenbaugh et al. 2005, Christensen 2007). These climate changes are likely to result in changes in fire regimes and vegetation characteristics across a diversity of landscapes and ecosystems.

Implication 2: Climate changes may result in threshold shifts - large, abrupt, and persistent changes in landscape patterns and fire regimes.

We identified several climate tipping points beyond which landscape patterns and fire regimes were significantly and persistently different from current conditions. For example, the ratio of crown to surface fire in the East Fork Bitterroot River basin roughly doubled – in other words, the fire regime shifted from mainly surface fires to a surface and crown fire regime) when temperature shifts exceeded 3 °C, except under scenarios that included increased precipitation. Temperature increases above 3-4 ºC in MD-GNP, 2-3 ºC in CP-YNP, and 5 ºC for EFBR resulted in a significant loss in basal area, and the warmest and driest climate scenarios resulted in a shift from forest-dominated to shrub and grassland-dominated landscapes for all study areas

Implication 3: Climate-fire interactions may cause more rapidly occurring and persistent changes in landscapes than climate change alone.

Many studies predict changes in species distributions in response to changing climate (Lenihan et al. 2003, Parmesan and Yohe 2003, Lawler et al. 2006, Rehfeldt et al. 2006). Climate changes alone are likely to shift ecosystem dynamics at time scales of decades or longer (Allen and Breshears 1998), while disturbance processes such as wildfire have the potential to alter ecosystems on much shorter time scales of days to months (Overpeck et al. 1990, Seidl et al. 2011). Landscapes may be particularly sensitive to threshold shifts catalyzed by disturbance when climate drives changes in wildfire regimes outside of the historical range and variability, or where anthropogenic factors such as fire exclusion have substantially altered forests and fuels.

Implication 4: Land managers must be able to anticipate and respond to climate change tipping points in order to develop effective management strategies.

Knowledge of potential tipping points allows managers to plan for changes in fire severity and frequency that may occur when the climate reaches a predetermined threshold. Management actions such as fuel treatments or prescribed fire can be developed and implemented in anticipation of tipping points, in order to mitigate adverse effects of climate change on landscape structure and function. The development of ecologically appropriate and effective strategies is not an easy or straightforward task, and is made more complex by differences threshold sensitivities across ecosystem types. Modeling projects such as this one can be used to detect potential climate change tipping points, and can further be used to test provide information to organize thinking, game multiple scenarios, and gain qualitative insight on the range of magnitudes and direction of possible future changes (Millar et al. 2007).

VI. Relationship to other recent findings and ongoing work

Our findings correspond to other ongoing work on climate change, fire, and ecosystem thresholds. For example, Falk et al. (In press) hypothesize that interactions of climate change and severe disturbance are more likely to trigger abrupt ecosystem transitions than either process in isolation, and as noted by as noted by Flannigan and others (2000) “The almost instantaneous response of the fire regime to changes in climate has the potential to overshadow importance of direct effects of global warming on species distribution, migration, substitution and extinction... fire is a catalyst for vegetation change.” Where climate changes produce temperature and precipitation regimes that are outside of the long-term range and variability we may expect to see changes in wildfire patterns and vegetation communities that strongly influence ecosystems; e.g. more frequent, larger, or higher-intensity wildfires may result in functional vegetation shifts from forest to shrub-dominated communities (Westerling et al. 2011), or can cause shifts in predominance of species toward those more highly adapted to frequent fire regimes (Loehman et al. 2011). Our simulation results point toward changes in fire regimes (area burned, fire type) that may occur with changing climate, and relate decreased landscape basal area to shifts in fire patterns toward increases in burned area and/or increased incidence of crown fires. Kitzberger and others (2012) simulated landscape dynamics under varying fire regimes and found that new landscape configurations resulting from severe disturbance may be highly resistant to recovery toward pre-disturbance conditions. Our results support this finding as well – the significant changes in basal area that occurred with climate changes were measured for the final year of our simulations, suggesting that the cumulative effects of climate and fire changes in our study landscapes catalyzed persistent shifts with no recovery.

Westerling and others (2011) and Smithwick and others (2010) modeled climate change, wildfire, and landscape interactions in Yellowstone National Park, USA. Both studies forecast mid-21st century shifts in fire patterns, including a decrease in the number of fire-free years, increased frequency of regionally synchronous fires and occurrence of extreme fire events, and increased total area burned. Modeled changes in fire regimes were posited to favor the establishment of low montane woodland or grassland-dominated vegetation types over the current forests, with less woody biomass (carbon) than is present in current vegetation communities. Projected fire patterns in these studies were based on a statistical model relating climate variability to the incidence of large fires and total burned area, relationships that were then applied to future climate projections from downscaled GCMs. Changes in vegetation were inferred from changes in fire regimes that could limit forest recovery post-fire, such as increased fire frequency and extent. In contrast, the FireBGCv2 model employs a mechanistic, process-based approach that explicitly simulates changes in wildfire patterns in response to climate changes, influence of climate changes on tree growth and mortality, and fire effects on forests; thus, the model is capable of simulating the complex feedbacks that occur between vegetation and fire regimes. As with the studies above, our results demonstrate that climate changes are likely to increase fire frequency and total burned area, but that shifts in fire regimes are highly dependent on amount of warming and accompanying shifts in precipitation. We found potential for threshold shifts toward non-forested landscapes with warmer and drier conditions, caused by increased tree mortality from fires as the amount of burned area increased. The mechanistic nature of the FireBGCv2 model provides the potential for a more detailed exploration of climate-fire-vegetation interactions in Yellowstone National Park and other forested regions, including timing of threshold responses, effects of fire and fuels treatments in future climates, and assessment of individual species responses to climate and wildfire changes.

VII. Future work needed

At the center of future simulation research is a need for comprehensive data to run and validate future models. The balance of data needs versus model advancement reflects an imperative for collaboration between field ecologists, who provide data and equations, and modelers, who must then integrate that knowledge to provide descriptions of phenomena at different spatial and temporal scales. It is critical that extensive field programs be intimately integrated with simulation efforts to ensure sufficient parameter and validation data are measured for model applications. Temporally deep, spatially explicit databases created from extensive field measurements are needed to quantify input parameters, describe initial conditions, and provide a reference for model testing and validation, especially as landscape fire models are ported across large geographic areas and to new ecosystems (Cary et al. 2006). For example, Hessl and others (2004) compiled a number of ecophysiological parameters for use in mechanistic ecosystem models, which has increased parameter standardization and decreased the time modelers spend on parameterization. New sampling methods and techniques for collecting data are needed to ensure the right variables are being compared at the right scales. Field data that are useful in simulation modeling should be stored in standardized databases, such as FIREMON (Lutes et al. 2006) and stored on websites so that they are easily accessible for complex modeling tasks. Last, new instruments are needed to quantify important simulation variables such as canopy bulk density, to initialize and parameterize fire behavior models (Keane et al. 2005). Model validation and verification are difficult tasks with landscape models that simulate vegetation and fire dynamics over millennia time spans (Keane and Finney 2003). There is a lack of spatially explicit, historical time series data that are in the right context to compare with model results, particular because this validation data must include multiple ecosystem characteristics.

VIII. Deliverables crosswalk table

Proposed	**Delivered**	**Status**
Peer reviewed journal papers	(1) Modeling effects of climate change and fire management on western white pine *(Pinus monticola*) in the northern Rocky Mountains, USA. 2011. *Forests* 2(4):832-860. (2) Modeling climate change and disturbance interactions: Effects on whitebark pine (*Pinus albicaulis*) and implications for restoration, Glacier National Park, Montana, USA. Proceedings – Symposium on the Future of High-Elevation Five-Needle White Pines in Western North America. 2011. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station Proceedings RMRS-P-63. (3) Climate-wildfire interactions potentiate ecological tipping points (4) Detecting critical climate-driven thresholds in landscape patterns and processes using spatial simulation modeling	(1) Completed (2) Completed (3) Draft Ms in progress (4) Draft Ms in progress
General Technical Report	A research simulation platform for exploring fire and vegetation dynamics: The FireBGCv2 landscape fire succession model. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-255. 137 p.	Completed
Improved FireBGCv2 program	Available at https://collab.firelab.org/software/projects/firebgc/files and ftp://ftp2.fs.fed.us/incoming/rmrs/missoula/ifsl/keane/firebgcv2/bin/	Updated as needed
Manager protocol	Climate change tipping points in fire management: Implications for forested landscapes	Ready to submit
Additional	**Delivered**	**Status**
Website	http://www.firelab.org/firebgcv2-tipping-points	Updated as needed
Formal presentations at national and international conferences	(1) (2009) Estimating critical climate-driven thresholds in landscape dynamics using spatial simulation modeling: climate change tipping points in fire management. Association for Fire Ecology Fire Congress, Savannah, GA (2) (2010) Are there "tipping points" in landscape dynamics with changing climates? A simulation modeling experiment. US-IALE Twenty-fifth Anniversary Symposium, Athens, GA. (3) (2010) Simulating fire dynamics and climate change in Glacier National Park, Montana, USA: Understanding the role of disturbance in predicting climate change effects on whitebark pine. High-Five Symposium, Missoula MT. (4) (2011) Modeling Effects of Climate Change and Fire Management on Western White Pine (Pinus monticola) in the Northern Rocky Mountains, USA. Association for Fire Ecology, Interior West Conference, Snowbird, UT November 14-18). (5) (2012) Estimating critical climate-driven thresholds in landscape dynamics using spatial simulation modeling: Do climate and fire interact to produce ecological tipping points? Association for Fire Ecology Fire Congress, Portland, OR	(1) Completed (2) Completed (3) Completed (4) Completed (5) Proposed for special session
FireBGCv2 Users' workshop	(2009) FireBGCv2 Users' Group Workshop. Missoula Fire Sciences Lab, Missoula, MT.	Completed

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